Acoustic Monitoring of First Responder's Physiology for Health and Performance Surveillance

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ABSTRACT

Acoustic sensors have been used to monitor human physiology to assess health and performance. Soldiers, firefighters, and other first responders often have very strenuous and demanding missions in environments that are hazardous to their health. Heart rate variability, breath rate, blood pressure, activity, and other parameters can be continuously monitored with acoustic sensors and transmitted for remote surveillance of personnel status. Body-worn acoustic sensors located at the neck and wrist do an excellent job at detecting heartbeats and other physiological parameters. However, they have difficulty extracting physiology during rigorous exercise or movements due to the motion artifacts sensed. Rigorous activity often indicates that the person is healthy by virtue of being active, and injury often causes the subject to become less active or incapacitated making the detection of physiology easier. One important measure of performance, heart rate variability, is the measure of beat-to-beat timing fluctuations derived from the interval between two adjacent beats. The Lomb periodogram is optimized for non-uniformly sampled data, and can be applied to non-stationary acoustic heart rate features (such as 1st and 2nd heart sounds) to derive heart rate variability and help eliminate errors created by motion artifacts. Simple peak-detection above or below a certain threshold or waveform derivative parameters can produce the timing and amplitude features necessary for the Lomb periodogram and cross-correlation techniques. High-amplitude motion artifacts may contribute to a different frequency or baseline noise due to the timing differences between the noise artifacts and heartbeat features. Data from a firefighter experiment will be presented.

Keywords: Acoustic, physiology, heart, sensor, performance, firefighter, blood pressure, breath, activity, soldier.

INTRODUCTION

The following scene could be taken from any action adventure movie: *"The young Lieutenant stood silent and still outside of the doorway waiting for the signal from his teammates to kick in the door and begin what may be the firefight of his life. He is one of many, poised to react. Smoke already filled the air, and the sense of impending danger further quickened his heart -- already racing under the load of his specialized equipment. He is breathing loudly, and his hands are firmly clenching the gear that he was taught would ensure his own survival. He knows there are people inside. He has trained many years for this, and when others might hesitate, he is ready to boldly go in. It's his calling. He was destined to become a …."* firefighter, soldier, SWAT team member, or law enforcement officer are among a few occupations that fit this scenario. This script describes the pride and dedication first responders have every time they are called to serve. They willingly put their lives on the line to do what is right and often heroic. Danger is always present, and it is our duty as hardware developers to do whatever it takes to ensure their safety and well-being. Today's technology can ensure tomorrows successful mission.

The Army Research Laboratory has developed a unique body-contacting acoustic sensor that can monitor the health and performance of firefighters and soldiers while they are doing their mission [1]. A gel-coupled sensor has acoustic impedance properties similar to the skin that facilitate the transmission of body sounds into the sensor pad, yet significantly repel ambient airborne noises due to an impedance mismatch. This technology can monitor heartbeats, breaths, blood pressure, motion, voice, and other indicators that can provide vital feedback to the medics and unit commanders. Acoustic signal processing techniques can be developed to recognize physiological events such as cough, gag, wheeze, and vomit, which may be indicators of hazardous material effects, biological or chemical weapons, or other severe medical condition. Energy calculations on sensor data resulting from footfalls, hand movements, head turns and general torso movement often create signatures that indicate how active a person is, or from a casualty surveillance point of view, that they are still moving or active.

Useful for soldiers, firefighters, and law enforcement, the sensor system can transmit physiology to remote locations for health and performance assessment. This can be done with dedicated transmitters, or by superimposing either the data or processed parameters over existing radio communication hardware and local data networks. In addition to physiology, the sensor is optimally suited for monitoring speech for voice communications or automatic speech recognition for computer controls. Much of ARL's prior emphasis has been to put sensors on soldiers to monitor them while they are doing their mission. Larger Army programs such as Land Warrior, Objective Force Warrior, Warfighter Physiological Monitor, Warrior Medic, and Future Combat System of Systems will also benefit from the ability to monitor physiology, voice, and activity. The patented technology will benefit the commercial sector for ambulatory health monitoring [2].

EXPERIMENT DESCRIPTION AND HARDWARE

ARL conducted an experiment at the University of West Virginia's Firefighter Training Academy in Morgantown, WV. Firefighters from the Clarksburg fire department volunteered to be monitored during their training in the burning building facility. Two scenarios were developed for the experiment. The first experiment, which will be termed the smoke-test, required the firefighting team to crawl/walk through a smoke-filled two-story building with an uncharged 1.5-inch hose to search for and rescue a mannequin (located on the second floor). Once the mannequin was brought down the stairs and outside, the firefighters then went back to where they found the mannequin and brought the hose back out. Burning hay in a 55-gallon drum created the smoke. The second experiment, termed the fire-test, required the firefighters to enter a smoke-filled building to locate a disoriented firefighter on the first floor whose alarm was sounding, escort him to safety, then proceed upstairs to put out the fire with the 1.5 inch hose. Burning several pallets and wood pieces created the fire and smoke. In addition to the two-firefighter team being tested, facility safety personnel with radios were inside the building observing the test with a thermal imager, and several firefighters were on standby outside the building in full gear. The building was also equipped with vents and shutters to immediately evacuate the smoke and intense heat in the event of an emergency. Two different firefighters were monitored during both scenarios. Vital statistics were taken on the two individuals prior to and after the test by a registered nurse.

The purpose of this test was to see how well the acoustic sensors monitored physiology amidst the intense activity and environment. Data was collected for post-processing. Sensors, data acquisition hardware, and data transmitter were attached to one firefighter, who was the lead of the team and was at the nozzle of the hose. Digitized data was stored on a small body-worn computer as well as digitally transmitted to another laptop in a safe location. The equipment used on this test allowed for redundancy of acoustic sensors and data acquisition, but would not be present for a fielded system. In addition to the acoustic sensors, electrocardiogram (ECG) sensors were used to verify the heart rate, temperature sensors quantified the thermal ambient environment, and a microphone characterized the ambient noise.

Figures 1 and 2 show the gel-coupled neck acoustic sensors and it's positioning in this test below the hood. Two sensors were chosen for redundancy and noise canceling features. Heartbeats, breaths, and voice all appear simultaneously at the two sensors, but motion artifacts may be out of sync and different in signature. Figures 3 and 4 show how the mask acoustic sensor is attached. Although Velcro was a field expedient solution in this test, the sensor could ultimately be build into the helmet, hood, or mask itself for similar contact. An acoustic sensor in the mask position picks up heartbeat pulses from the temple, breath sounds through sinus and tissue conduction, voice, coughing, wheezes, and activity.

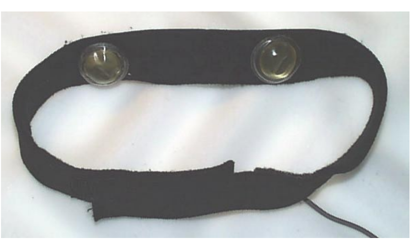

Fig. 1: Neck sensor strap

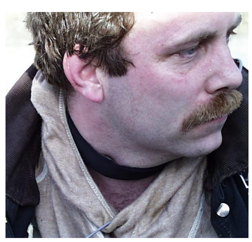

Fig. 2: Sensor on neck

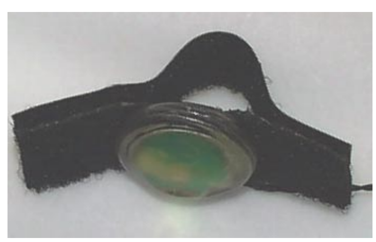

Fig. 3: Mask sensor

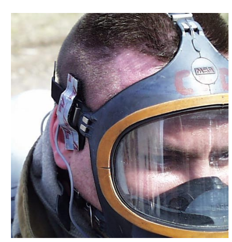

Fig.4: Sensor on mask

Figures 5 and 6 show the wrist acoustic sensors in a wristband embodiment. In proximity to the sensor were positioning mechanisms to ensure the band did not rotate, and kept the sensor over the radial artery for strongest signal positioning.

The wires leading from the left and right wrist sensors to the data logging hardware can be seen in figure 7. Figure 8 shows the nylon pack that contains all the hardware, and the firefighter's jacket in figure 9 protects the equipment while the firefighter is being monitored. The location of the equipment on the torso was chosen by the firefighters as an area that would not interfere with the breathing equipment or hose usage, and not be uncomfortable while they were crawling most of the time. Figure 7 also shows the seven-lead (three channel) ECG pads and wires, along with a commercially available Polar Heart Monitor chest band often used by runners. The Polar product has reduced many of the motion artifact problems associated with ECG's, but provides only an indicator signal and not the true ECG waveform. The three-channel ECG data is stored on the Holter Monitor's PCMCIA memory card seen in the left hand side of figure 10. The 1st channel of the ECG is also fed into the computer's data acquisition card.


Fig. 5:Wrist sensors


Fig. 6: Sensor on wrist


Fig. 7: ECG/Polar sensors

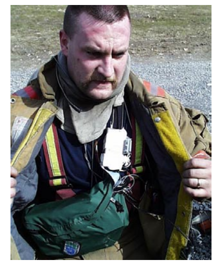
Fig. 8: Hardware


Fig. 9: Full gear

Figure 10 shows the Holter monitor and ECG leads, the bipolar electrode Polar chest strap transmitter and inductive pick-up, the acoustic mask sensor, the acoustic neck sensor strap, the boom microphone, the temperature probe, two acoustic wrist sensors, and the BioRadio digital data transmitter. Figure 11 has another view of the transmitter, the PCMCIA eight-channel data acquisition card that goes into the Libretto hand-held computer. Underneath the computer is the preamplifier and anti-aliasing filter for each sensor prior to digitization by the National Instruments DAQ-card.


Fig. 10: ECG logger, sensors and transmitter


Fig. 11: Computer, filters, transmitter, and sensors


Fig. 12: 1st floor stairs


Fig. 13: Dragging mannequin


Fig. 14: Firefighter acting unconscious

Figure 12 shows the inside of the burn building, and the stairway that the firefighters navigated through with the hose and mannequin. All doors and windows were closed during the exercise, making visibility essentially zero. The thermal imagery from the safety officer's camera was transmitted outside the building for recording of truth data and for participants to observe the firefighters in action. The firefighters crawling through the building could not see a foot in front of them, as determined by observing their hand motions searching through the smoke and not being able to find people, structure, or objects only inches past their reach. Figure 13 demonstrates the smoke thickness as the smoke-test team drags the mannequin out of the smoking building. Figure 14 shows a firefighter pretending to be unconscious in order to collect physiological and movement data that might simulate a downed-firefighter.

Figure 15 shows the first team entering the building with a charged 1.5-inch hose for the fire-test. After they locate the disoriented firefighter by the sounds of his alarm, they begin to escort him out past the smoking-drum shown in the thermal image of figure 16. Once the disoriented firefighter is safe, they then extinguish the fire on the second floor, as seen with the thermal imagery in figure 17. Keep in mind that the building is completely filled with smoke, and that the firefighters have maneuvered mostly by touch. The clarity and details of the thermal imagery presented in figures 16 and 17 are not available to the firefighters doing the task; they can't see anything. These images help demonstrate the absolute need for firefighters to have thermal imagers when entering smoke-filled buildings.

Fig. 15: Enter fire test

Fig. 16: IR image of disoriented firefighter

Fig. 17: IR image of fire being extinguished

DATA AND RESULTS

Figure 18 shows the ECG derived heart rate from both firefighters doing both scenarios. Firefighter number one reached an average heart rate of 165 beats per minute (BPM) while dragging the mannequin to safety, whereas he only reached 152 BPM while putting out the fire. Firefighter number two reached an instantaneous maximum heart rate of 182 BPM while maneuvering the mannequin in the smoke-test, and 168 BPM during the fire-test. Note also that firefighter number two's resting heart rate (between smoke and fire events) stayed near 110 BPM, whereas firefighter number two was able to get below 100 BPM during the rest period. Prior to the first test, both firefighters' heart rates were approximately 80 BPM. The ability to monitor this resting heart rate, when the physiological signal-to-noise ratio (SNR) is very good, is in itself is an important tool, in that it can be a good indicator of which firefighters are ready to reenter a building fire or need to be relieved. The duration of elevated heart rates and the maximum rate achieved can also be an indicator of a firefighter's ability to safely and effectively perform his or her mission.

Firefighter #A: Smoke filled building/manequin rescue
Firefighter #B: Find disoriented firefigther/put out fire

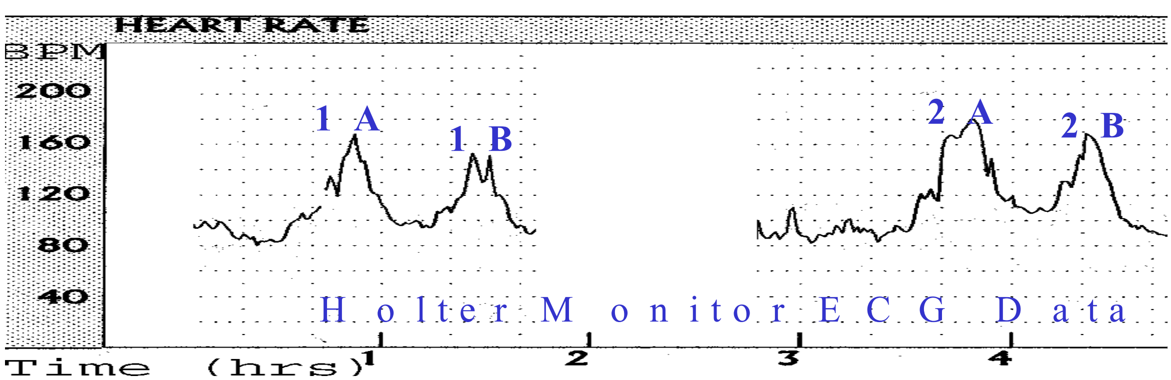

Fig. 18: ECG data showing heart rate for each firefighter

Figures 19 and 20 show an air temperature profile of the smoke-test and fire-test, respectively. It is apparent from the data that the temperature probe used was having some intermittent problems as seen by the “drop-out” sections. This probably resulted from the fact that the Polar heart rate indicators were superimposed on the DC temperature level to store more information on a single channel, and must have had some circuit interactions. However, the general trend and values are believed to be correct. For the smoke test the cold concrete building had not heated up much due to the burning hay and the ambient air got cooler as the firefighter first entered and was on the ground of the first floor. The temperature was higher on the upper floor. Figure 20’s fire-test temperature data shows that the ground floor is warmer than the previous smoke-test due to the pallets burning, and the hottest temperature reached while standing near the fire was approximately 125 degrees Fahrenheit. This firefighter admitted that this particular fire was not too hot, in that the amount of wood and duration of burn had not really heated the building up too much. However, knowledge of heat exposure can be an important measure, and may be able to predict thermal stress and dehydration.

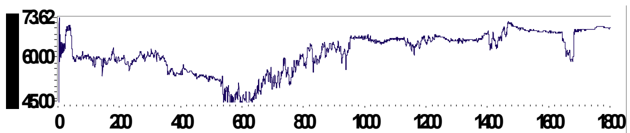

Fig. 19: Temperature for smoke test

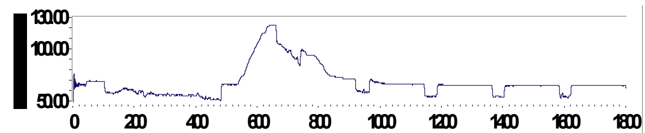

Fig. 20: Temperature for fire test

Figure 21 shows a representative 24-second section of data that was stored on the body-worn computer. High bandwidth data was collected to accurately extract heart and breath sounds. The data was sampled at 1500-Hz, with an anti-aliasing filter corner frequency of 500-Hz. Eight channels of data were streamed to the hard drive of the computer for 30-minutes, or 1800-seconds. A new file was started for each firefighter and each test scenario. Channels 1 and 2 are the left and right acoustic neck sensors, channels 3 and 4 are the left and right acoustic wrist sensors, channel 5 is the boom microphone, channel 6 is the acoustic mask sensor, channel 7 is the Polar heartbeat indicators with a DC voltage shift superimposed for temperature, and channel 8 is the ECG signature. Notice the clearly defined heartbeats in the neck, wrist, mask and ECG traces. The left and right neck data are essentially symmetric, with some simultaneously occurring motion artifacts in the 800- and 802-second region. Notice, however, when comparing the left and right wrist data, that the left wrist has intense activity between 795- to 800-seconds, but the right wrist has the activity between 785- and 790-seconds. This alternating wrist activity was present often in these scenarios, and is indicative of the firefighter crawling on the floor (the jarring motion artifacts from using alternating hands to support him as he crawled). Very often the amplitude of the intense activity exceeded the maximum input range for the data acquisition and was clipped. The data shown in figure 21 was manually ranged to highlight the lower-level physiology, and not necessarily show the clipped intense activity. Although clipping of the data is undesirable from a data processing point of view, it does indicate that the firefighter is still active and involved in some form of intense motion. In its simplest form, one might conclude that if he is still moving, he is still healthy, regardless of whether the physiology is visible amongst motion artifacts. The heartbeats from the acoustic mask sensor are clearly visible at the beginning of this set, but are less apparent when the crawling activity starts. The mask physiology is often lost due to firefighters constantly turning their heads while maneuvering, and resulting motion of the breathing hose, mask, and helmet were transmitted through the mask straps to the sensor. The SNR of the heartbeat physiology at the head is not a strong as at the neck. Notice also the ECG suffers from motion artifacts during the intense motion sections. Some of these artifacts are removed with appropriate filtering, and using electrode patches better suited for long-term exercise and restricting lead motion should also improve the ECG data. The Polar heartbeat indications are very good even during significant activity.

The data in figure 21 shows very clear acoustic heart signals with distinct peaks for determining the inner-beat-intervals (IBI’s). For example, a person with a short-time average heart rate of 60 BPM might have ten beats spaced exactly 1-second apart, or five beats slightly above and five beats slightly below 1-second intervals, with an irregular IBI sequence during that 10-second period. How the IBI’s fluctuate on a beat-by-beat basis, as well as long-term trends, is termed heart rate variability (HRV) and gives an indication of how well the body is regulating blood pressure, breathing, and core temperature [3]. These IBI’s also can indicate mental activity related to concentration on a task, such as when the IBI’s become very regular due to a task with intense concentration and precision muscle control, whereas the IBI’s may vary significantly for tasks with varying mental and physical distractions.

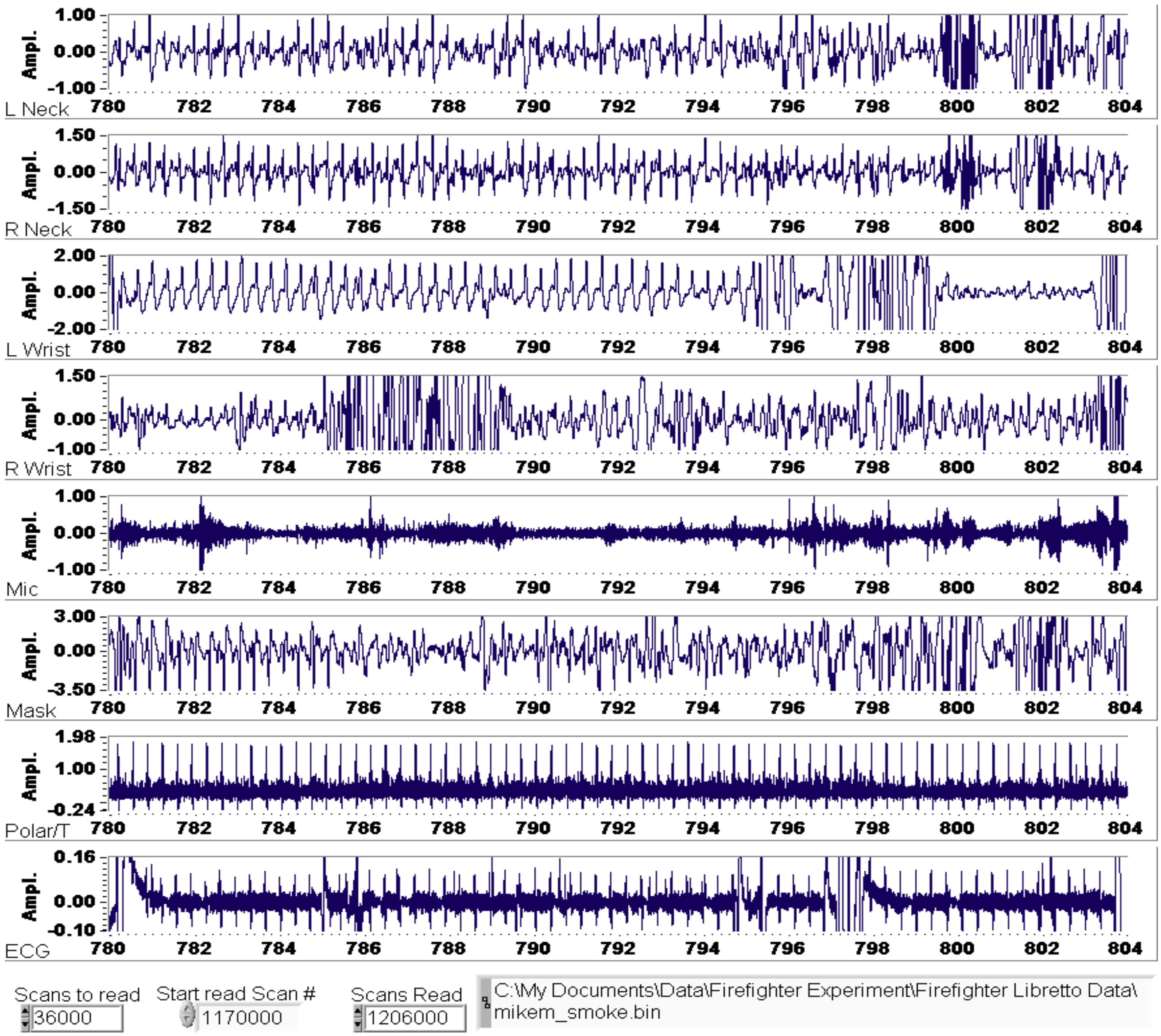

Fig.21: Twenty-four seconds of sensor data (top-to-bottom: L/R neck AC, L/R wrist AC, mic, mask AC, polar, ECG)

Figure 22 shows two seconds of data from the computer-based storage. Note the very clear indications of heartbeats on all physiological sensors. Of significant importance is the time-difference-of-arrival (TDOA) between the ECG and the neck and wrist acoustic pulses. The literature shows that changes in the pulse-wave-velocity (PWV) are directly proportional to changes in the systolic blood pressure [4]. The ECG monitors the electrical stimulus that creates a mechanical pressure wave that leaves the heart and travels through the arteries. The time it takes for the pulse to travel between two fixed locations (such as from the heart to the wrist) is directly proportional to the pressure of the blood (speed of sound in the artery changes with respect to density and the velocity component of the blood flow). By measuring the time-difference between the heartbeat indications from ECG-neck, ECG-wrist, ECG-head, neck-wrist, head-wrist, and neck-head, one can approximate the systolic blood pressure on a beat-by-beat basis. The neck and wrist acoustic sensors provide the largest length of travel (and delta-time), and therefore would permit best timing resolution with the lower sample-rates of wearable data acquisition systems.

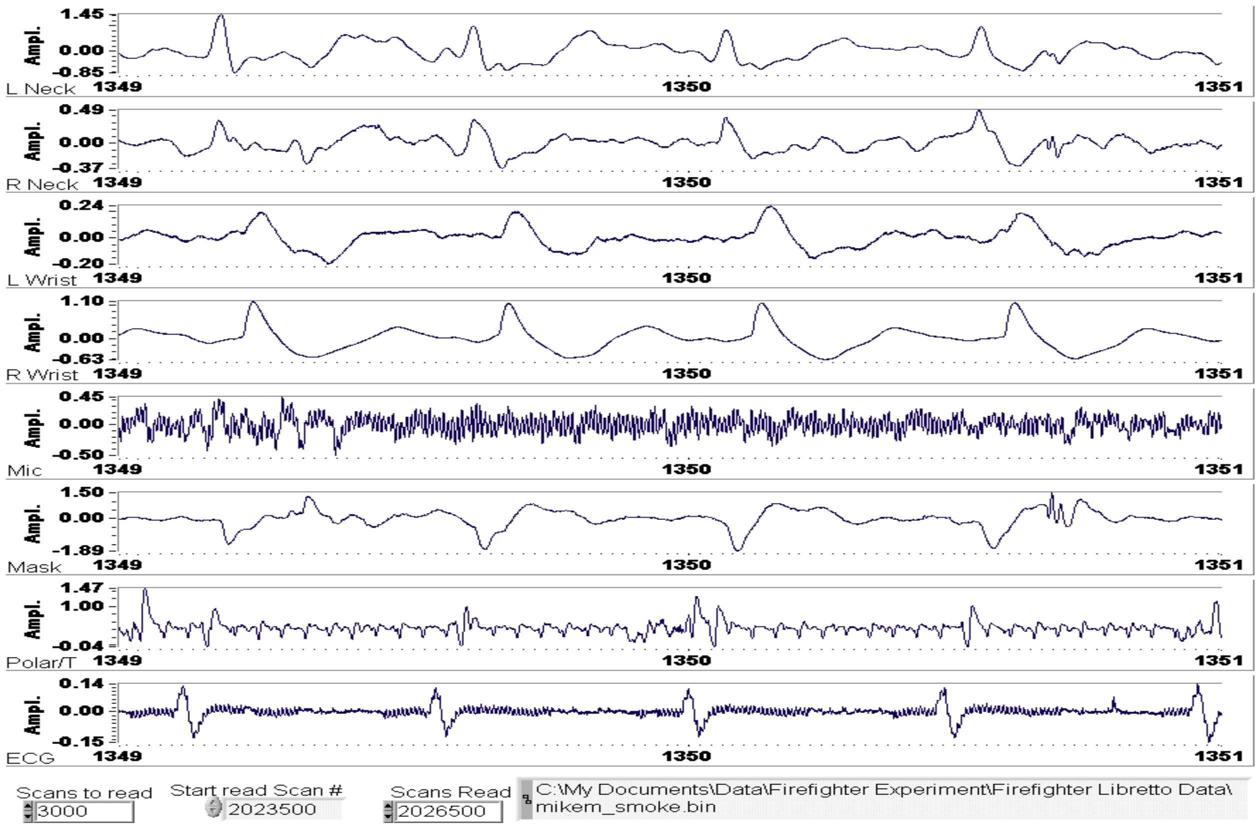

Fig. 22: Two seconds of computer stored physiology

The data from this experiment has sufficient SNR and timing resolution to calculate systolic blood pressure throughout. Blood pressure cuff measurements were taken at the beginning and end of the experiments and will be used after further analysis to calibrate the PWV measurements. These data have not been fully processed, but sample measurements of PWV were extracted from a few intervals within one of the test scenarios, and are shown in figures 23 and 24. Cross-correlation techniques between the wrist and neck acoustic sensor bring out the PWV time shift very well [5]. Note that the time-differences between the ECG waveforms and Polar heartbeat indications are a result of the Polar processor, transmitter, and receiver delays. Data in figures 23a and 23b show sample data points indicating the pulse wave velocity is changing with respect to blood pressure. In figure 23a the triangles represent the inner-beat-interval between ECG pulses, which is the inverse of the heart rate frequency (an IBI of 0.5-sec indicates a rate of 2 beats per second, or 120 BPM). From the IBI data (triangles), it can be seen that the heart rates vary from approximately 60 BPM at the beginning, 120 BPM in the middle, and 85 BPM at the later part of this 50 minute window of data. The squares indicate the time interval between ECG and wrist acoustic pulse. The diamonds are the time interval between ECG and neck acoustic pulse.

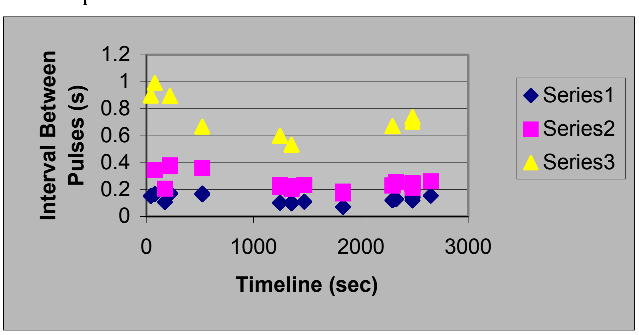

Fig. 23a: Sample event intervals (IBI, wrist, neck)

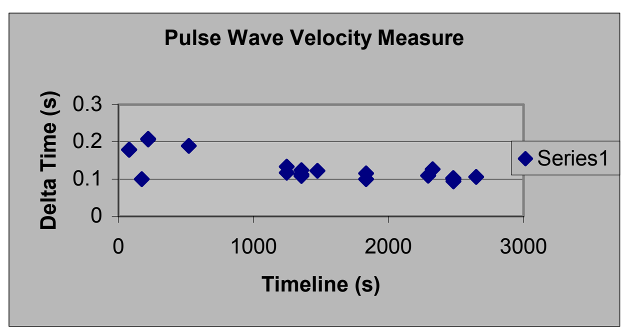

Fig. 23b: Time difference between neck & wrist pulses (PWV)

Figure 23b shows the delta-time between the neck and wrist acoustic pulses shown in figure 23a. A long time-delta indicates a slow wave (low systolic pressure) and a short time-delta indicates a fast wave (high systolic pressure). The trend in figure 23b shows the systolic blood pressure is increasing the entire experiment, as would be expected from the intensity of the smoke-test mission. Note also that the blood pressure is increasing even though the figure 23a's data shows the heart rate is decreasing at the end of the data set. The acoustic sensors and transmitters used in this experiment could have been built into a wristwatch and helmet headband, and provide the same data without the firefighter even knowing he or she is being monitored. The wristwatch alone could be worn continuously to monitor pre- and post-alarm heart rate, and activity. Work has been done in approximating systolic pressure from the slope of the second heart-sound, but it is not as accurate as the PWV technique since there are many physiological variables that also affect the pulse shape [6]. It is also possible that breath rates can be derived from acoustic pulses at the wrist by analyzing changes in amplitude that result from the lungs over- or under-pressurizing the heart. This phenomenon of decrease in pulse pressure during inspiration is called "pulsus-paradoxis", and is often associated with situations where respiration is labored [7]. The top part of figure 24 shows the RMS energy fluctuations from the neck's inhale and exhale sounds, the middle shows the acoustic wrist pulse peaks, and the bottom are the same acoustic wrist pulse peaks linked together. Note the similarity of amplitude variations of the wrist pulses and the breaths.

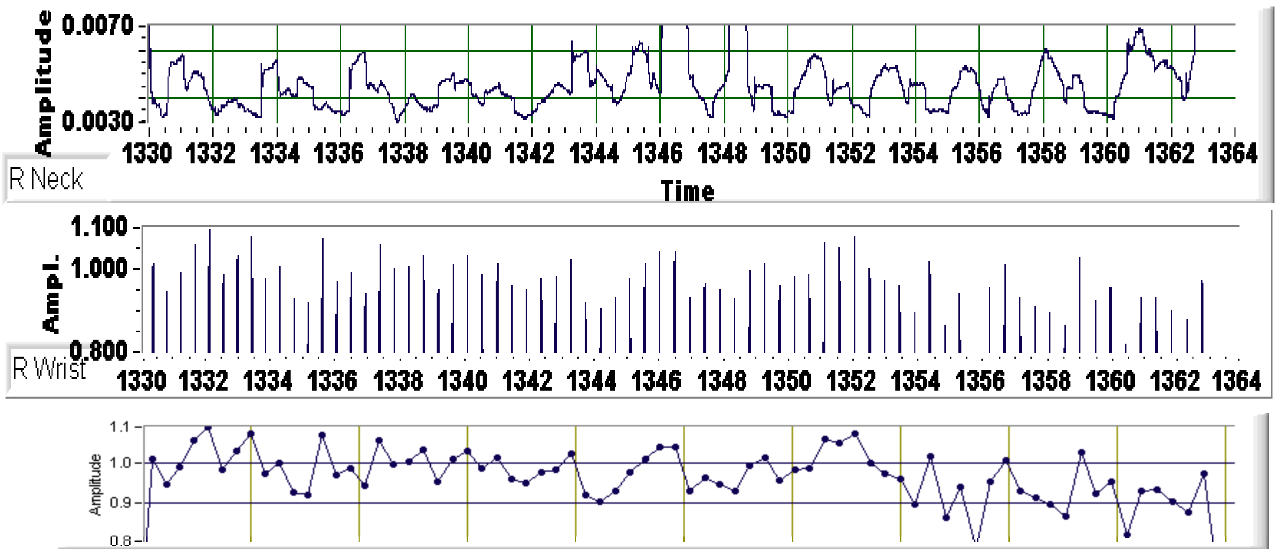

Figure 24: Breath pattern from neck sensor compared to breath rate derived from wrist pulse amplitude variations.

To give an indication of the quality of the acoustic signals and the spectral information contained with the waveforms, figure 25 shows time-frequency representations (spectrograms) for all eight channels of a 24-second segment that includes speech between 799- and 803-seconds. The vertical axis is frequency (Hertz) and the horizontal axis is time (seconds). The z-axis is amplitude (dB), where higher on the color-bar (on the right) represents louder amplitude. For example, the neck acoustic data clearly shows high-amplitude heartbeat pulsations in the low-frequency (0- to 120-Hz) region, high-amplitude harmonics of the voice structure, and medium-level broadband breath sounds in the 200- to 500-Hz region. The anti-aliasing filters can be seen to attenuate those sounds above 500-Hz. On the wrist acoustic spectrogram, pulses are clearly visible in the low-frequency region, as well as high-level motion artifacts in the 795- to 800-second region for the left hand, and in the right at 785- to 790-seconds. Comparing the ambient microphone data to the neck-acoustic data, the ambient microphone detects the alternating conversation between the two firefighters, yet the neck acoustic sensor completely rejects the other firefighters voice. The mask acoustic data clearly shows well-defined heartbeats, breaths, and voice, as well as some motion artifacts. The ECG data shows electromagnetic interference (EMI) susceptibility of the sensitive electrodes and wires, whereas the Polar device shows the processed heartbeat indications after intense narrow-band filtering has removed much of the EMI.

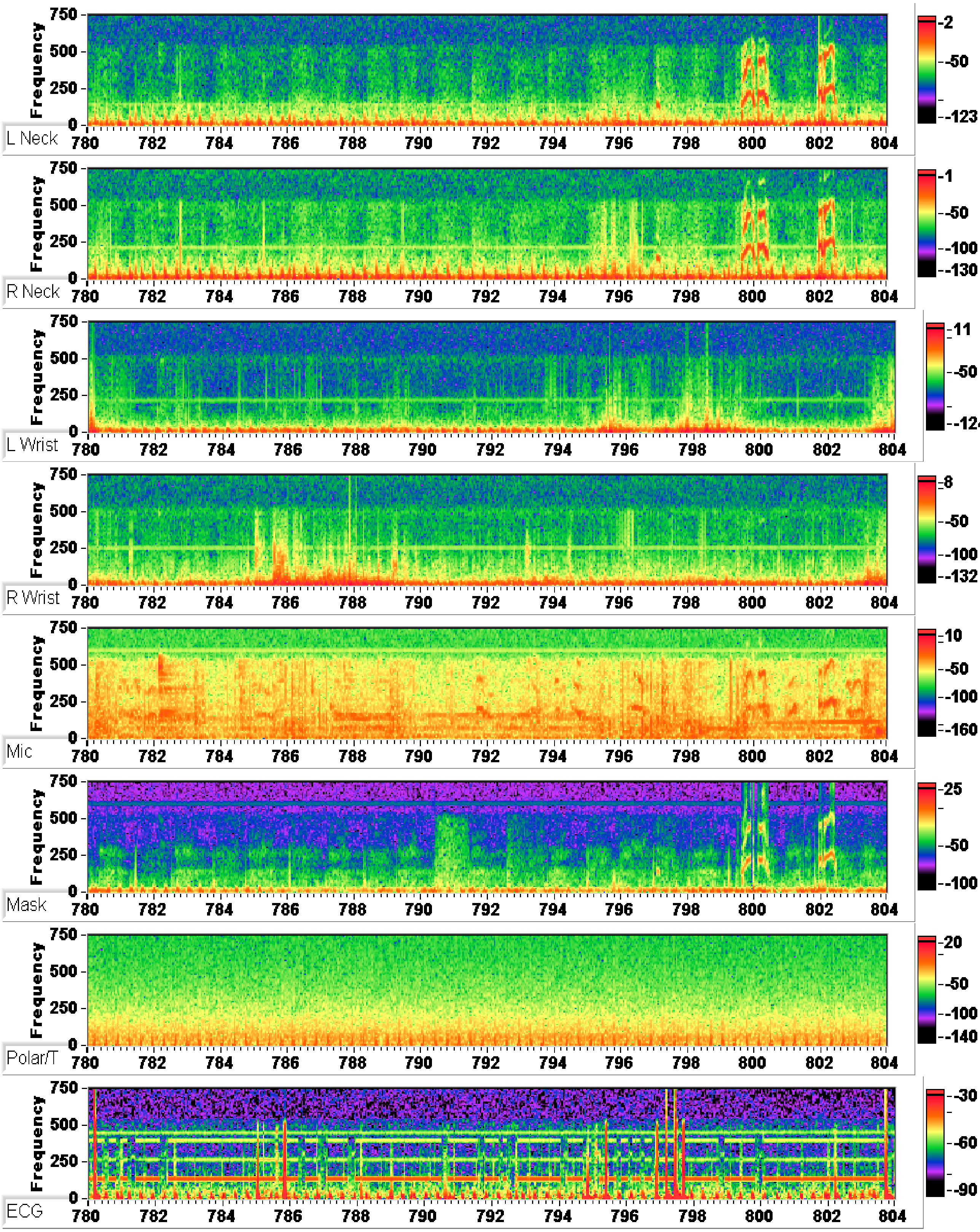

Fig. 25: Time-frequency analysis of computer stored data (top-bottom: L/R neck, L/R wrist, mic, mask, polar, ECG)

As mentioned earlier, ARL's gel-coupled sensor is excellent for voice reception. Figure 26 compares the neck-acoustic sensor (top) to the boom microphone (bottom) during speech. Both sensors detect intelligible speech, but the ambient noise rejection of the neck-contacting sensor is excellent and the voice SNR is higher with the neck acoustic sensor. The gel-coupled neck sensor has demonstrated significant SNR benefits over boom microphones for use with automatic speech recognition software such as HTK Entropic, ViaVoice, and Dragon Naturally Speaking [8].

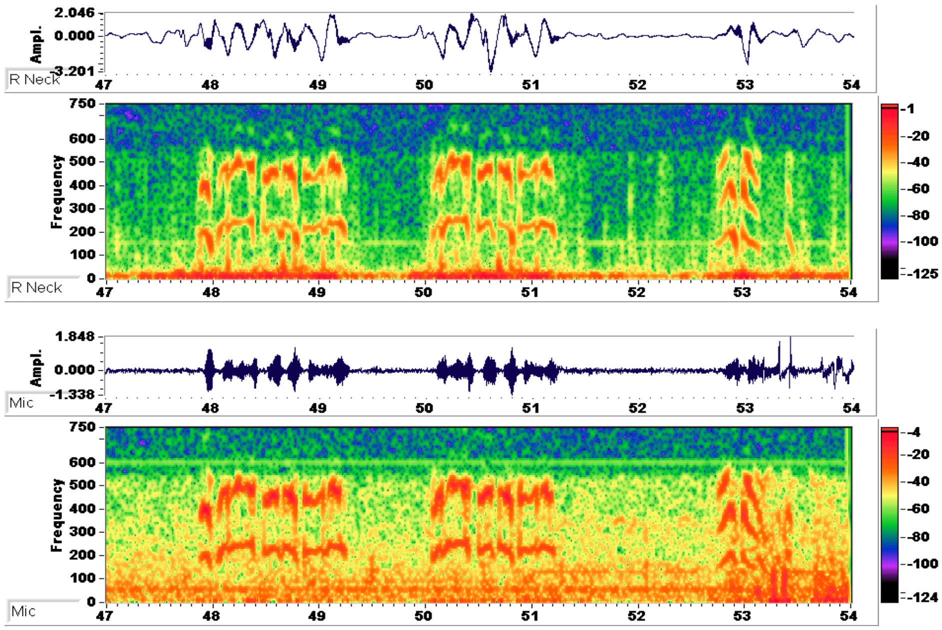

Fig. 26: Spectrogram comparing voice at neck (upper) and airborne mic (lower)

One method to monitor the firefighters is to look at short-term energy detected at the sensors. The higher the root-mean-squared (RMS) energy, the higher the activity. Figures 27 and 28 show RMS calculations on the wrist sensor data during the smoke-test. Figure 27 indicates when the firefighter was crawling, maneuvering the mannequin for extraction, and retrieving the hose after the mannequin was removed. Comparing the left and right hand graphs, one can even see that toward the end of the smoke-test, the firefighter was using his right hand much more vigorously than the left (likely holding the hose with the right hand). It is very evident from these two graphs that low-level activity is present amidst high-level activity. Had the high-level activity diminished significantly for a significant period, it would be readily apparent, and could cause an alert to be sent, much like the firefighters motions sensor already does. For comparison, figure 29 shows the RMS energy from the right neck sensor during the same period. High levels at the neck result from head turns, voice, jacket, hood, and mask movements, and muscular activity from lifting or crawling.

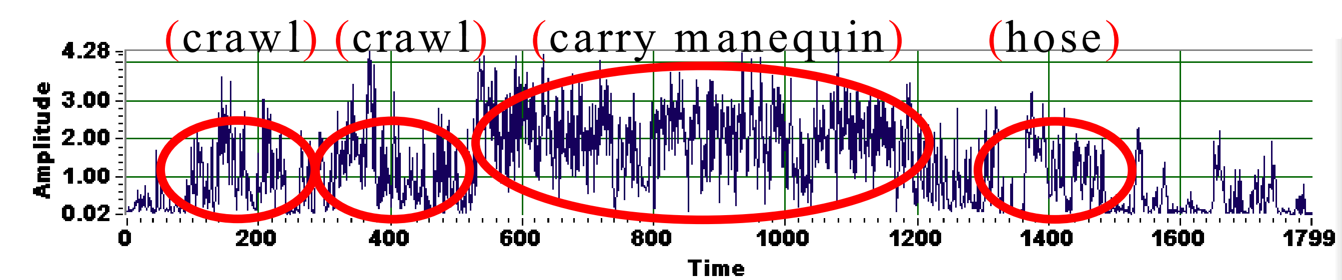

Fig. 27: RMS energy of left wrist sensor (30 minutes)

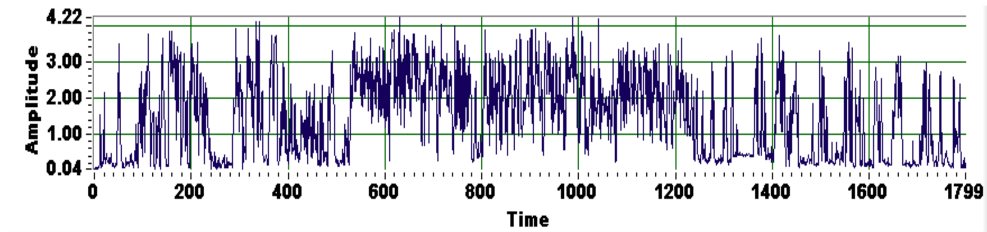

Fig. 28: RMS energy of right wrist sensor (30 minutes)

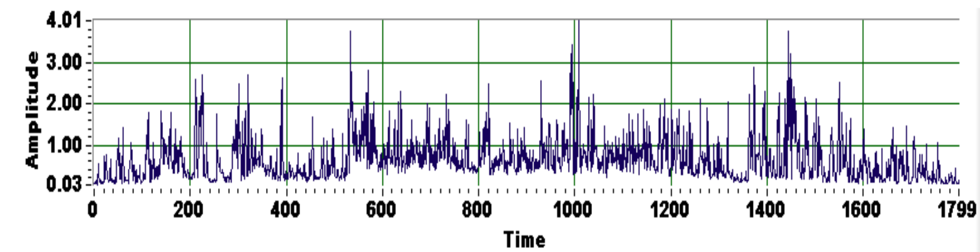

Fig. 29: RMS energy of right neck sensor (30 minutes)

The RMS energy graphs in figures 30 through 33 are from the fire-test, which took less than 20-minutes to complete. The data in figure 30 shows the RMS energy of the mask acoustic sensor, and clearly indicates when the firefighter took off the mask at the end of the scenario (he was asked to sit and relax for the remainder of the acquisition). The energy spikes occurring occasionally in the remaining section are from intense motion of the mask sensor itself during the rest period. This is an excellent indicator for whether the mask is on or off, possibly indicating a distressed firefighter condition. Having redundant energy measures at various locations on the body can verify that the firefighter is still active even though the mask acoustic sensor indicates unusually low-level activity.

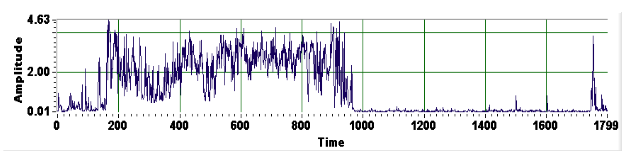

Fig. 30: RMS energy of mask sensor (fire experiment)

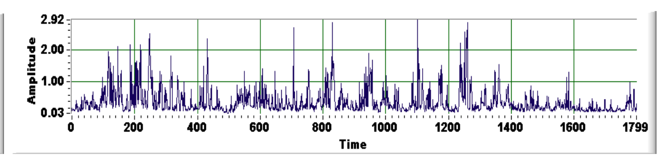

Fig. 31: RMS energy of microphone sensor (fire experiment)

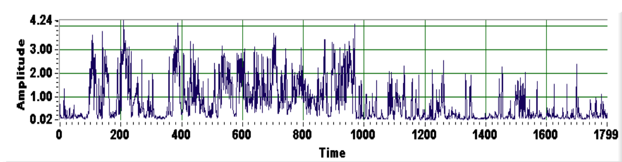

Fig. 32: RMS energy of R-wrist sensor (fire experiment)

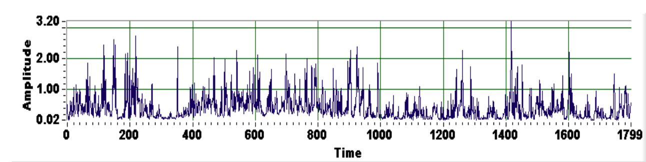

Fig. 33: RMS energy of L-neck sensor (fire experiment)

When a firefighter goes down due to injury, the SNR of the physiology improves greatly. This is when medical monitoring is needed the most. The decrease in RMS energy at all acoustic sensors will indicate a decrease in activity. Figures 34, 35, and 36 show time series and spectrograms of 80-seconds of data during a simulated unconscious firefighter. The first 20-seconds show him walking, standing, and then getting into position on the ground. He then holds as still as possible for approximately 40-seconds until his motion sensor alarm activates, then he gets up off of the ground. Figure 34 shows excellent heartbeats and breaths in the middle section with minimal motion artifacts. Figure 35 shows an increase in the amplitude of the neck heart sound, resulting either from more blood flow from being in the horizontal prone position, or because coupling pressure increased because of a change in neck band position or tension. Breath sounds are clearly visible throughout. Figure 36 shows wrist acoustic activity getting into position on the ground, excellent pulsations throughout the unconscious period, and intense wrist activity to get up at the end of the scenario.

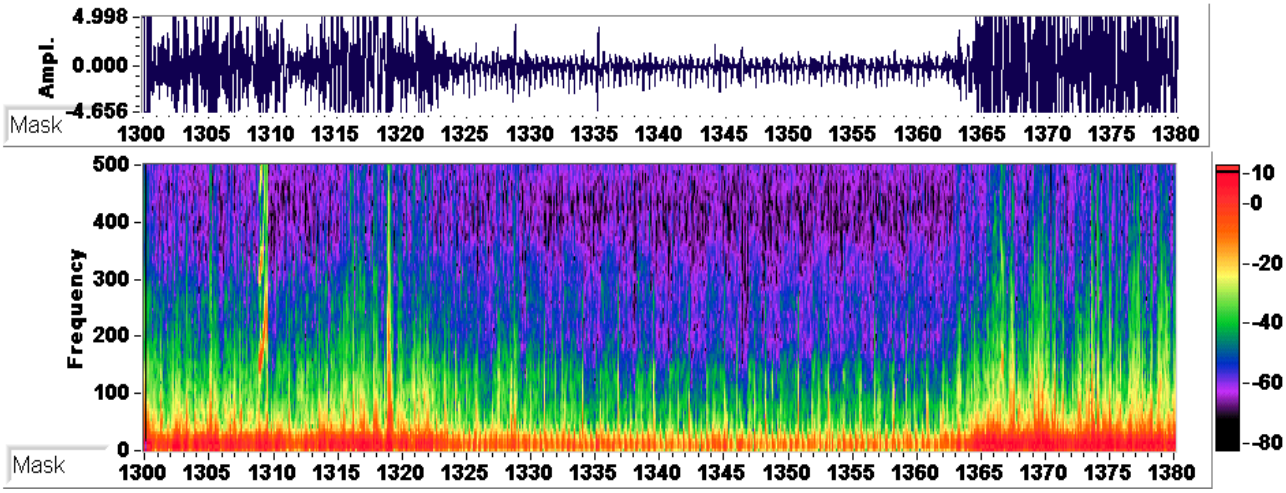

Fig. 34: Spectrogram and time-series of mask data during unconscious scenario

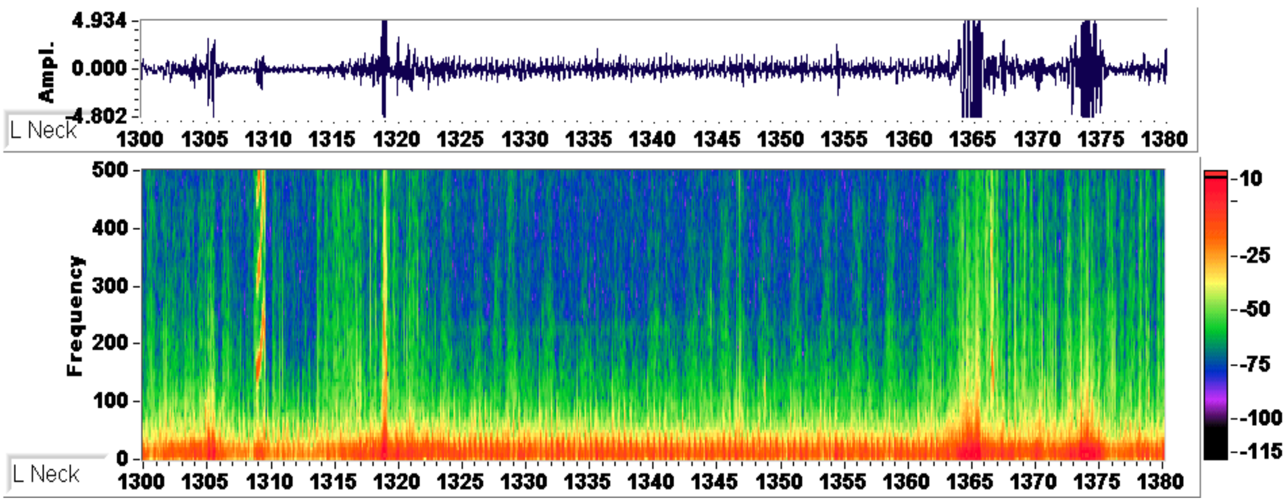

Fig. 35: Spectrogram and time-series of L-neck data during unconscious scenario

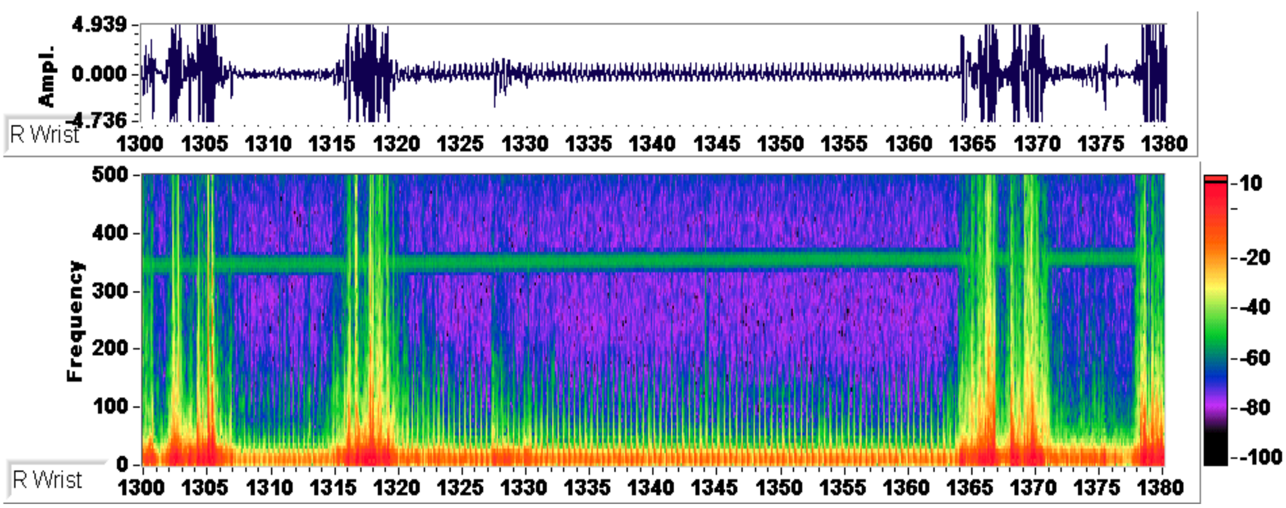

Fig. 36: Spectrogram and time-series of R-wrist data during unconscious scenario

As a simple example of breath rate detection, high-passed neck data reveals a lot of broadband high-frequency energy resulting from the airflow in the throat. Using Fast-Fourier Transforms (FFT's) to monitor the temporal fluctuations of the RMS energy produces a breath rate peak in the power-spectrum results. Figure 37 shows intentionally clipped time-series data from the neck sensor, and the resulting half-second sliding window RMS energy. The clipping of the data removes the influence high-amplitude motion artifacts have on the RMS calculation, and was clipped at a level of three times the median value of the absolute value of the band-pass filtered data. The band-passed spectrogram of figure 37 also shows the broadband breath cycles. Figure 38 is the power spectrum of the RMS energy for the 24-seconds shown. The 0.45-Hz breath rate represents a breath every 2.2 seconds, which is supported by the ten breath-cycles seen in the 24-seconds of data. Figures 39 and 40 show the simultaneously taken results from the mask sensor, showing the strongest signal at 0.45-Hz.

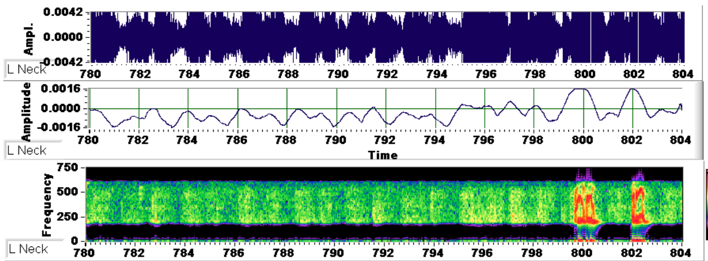

Fig. 37: Time, RMS, and band-passed spectrogram of L-neck

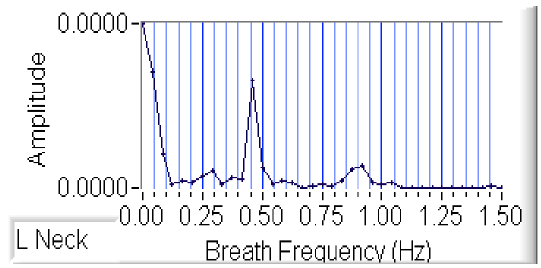

Fig. 38: Breath rate extraction from RMS data

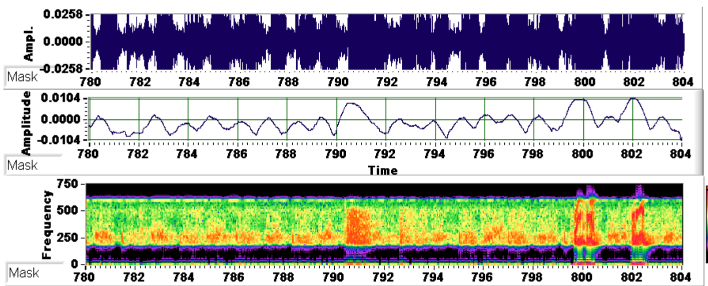

Fig. 39: Time, RMS, and band-passed spectrogram of mask data

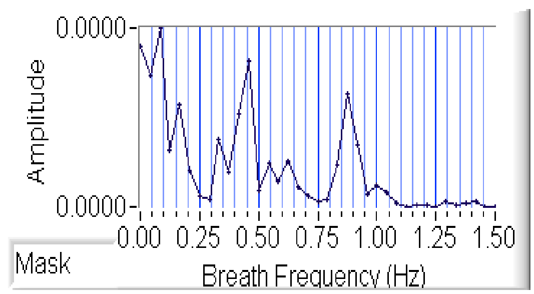

Fig. 40: Breath rate extraction from RMS data

The data depicted in figures 41 through 43 were transmitted from the firefighter and out of the building at 150 samples per seconds with a 50-Hz low-pass filter. This low-bandwidth data demonstrates the viability of transmitting physiology and general status of firefighter. Figure 41 shows 37.5-seconds from all eight sensors. Much of the rigorous activity data transmitted was saturated, but nevertheless provided activity level information. In the intervals when activity was low, the physiology is very evident, as seen in the 6.25-seconds of figure 42. Figure 43's 1.25-second window shows that the time resolution is adequate for pulse wave velocity measurement for systolic blood pressure approximations.

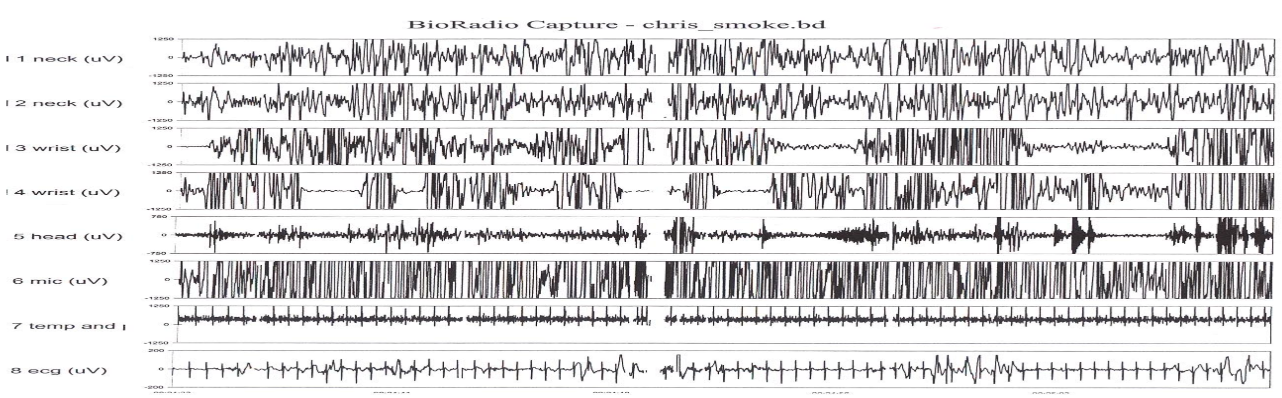

Fig. 41: Transmitted physiology (37.5 seconds)

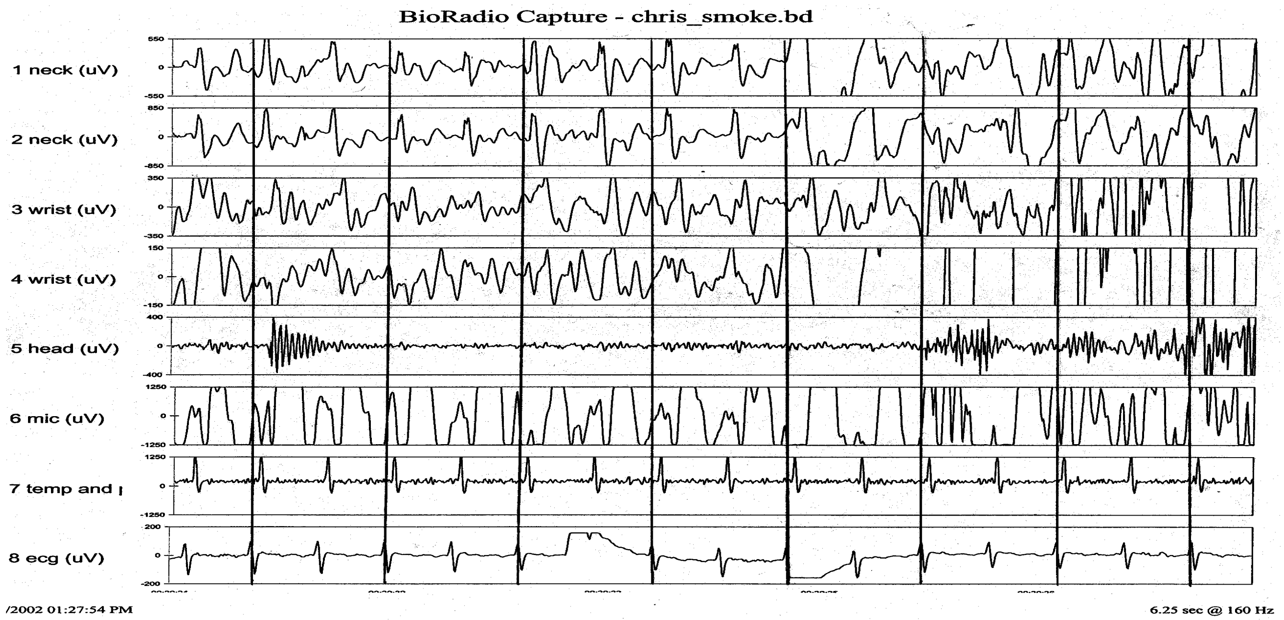

Fig. 42: Transmitted physiology (6.25 seconds)

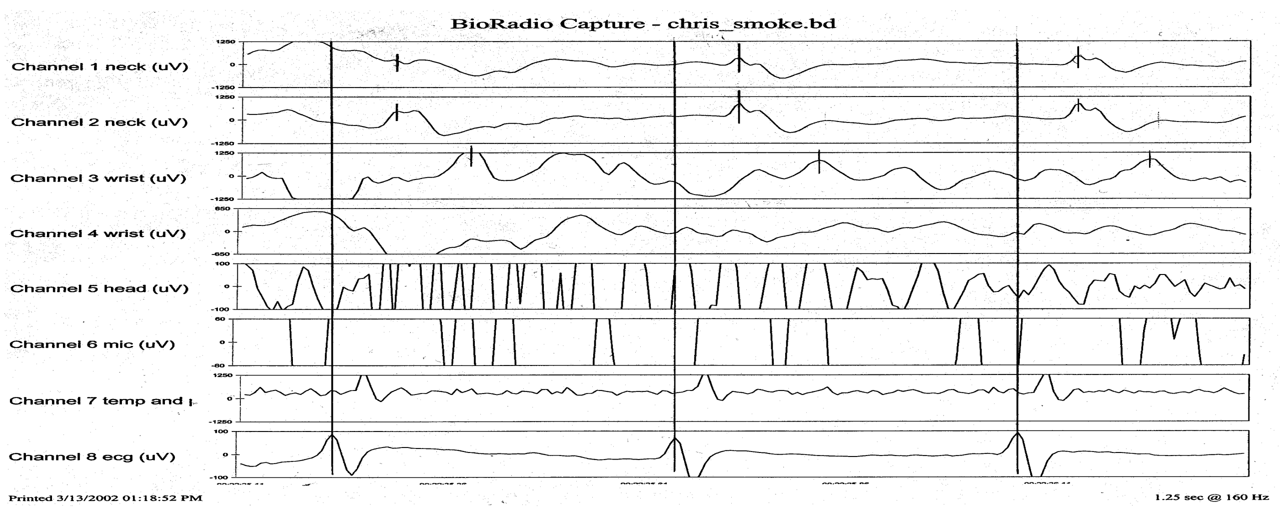

Fig. 43: Transmitted physiology (1.25 sec)

CONCLUSION AND FUTURE EFFORTS

Acoustic sensors and signal processing can extract much information about the firefighters health and performance. Transmitted data shows that heart rate, breath rate, blood pressure and activity can be monitored by medics/commanders at a remote location. The quality of the acoustic data is excellent, and can provide much more information than the ECG. RMS energy from the sensors indicates activity. Breath rates are measured from high-frequency broadband sounds at the neck or mask or pulse amplitude variations at the wrist. Timing (PWV) between two sensors indicates systolic blood pressure on a beat-by-beat basis. The IBI's give pulse rate and an indication of heart rate variability. The acoustic data from this test demonstrates that even though physiology is sometimes masked by motion and activity artifacts, is still provides useful indicators that the firefighter is still active and most likely functioning effectively. It is when the person being monitored ceases to be active or during resting periods that the acoustic SNR is exceptional for monitoring physiology. This is when vital signs monitoring is most important. Acoustic sensors and a transmitter will be incorporated into a garment, which will reduce some of the motion artifacts resulting from the cables and data logging equipment. It is felt that such a shirt could be worn continuously while firefighters are on call to monitor the stressful and demanding nature of their entire shift. The same shirt will be evaluated on soldiers and for home health monitoring. The data collected from the test described in this paper will be processed further to extract heartbeats, breaths, and blood pressure for the entire mission.

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